Charge-to-spin conversion of electron entanglement states and spin-interaction-free solid-state quantum computation

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Without resorting to spin-spin coupling, we propose a scalable spin quantum computing scheme assisted with a semiconductor multiple-quantum-dot structure. The techniques of single electron transitions and the nanostructure of quantum-dot cellular automata (QCA) are used to generate charge entangled states of two electrons, which are then converted into spin entanglement states using single-spin rotations only. Deterministic two-qubit quantum gates are also manipulated using only single-spin rotations with the help of QCA. A single-shot readout of spin states can be carried out by coupling the multiple dot structure to a quantum point contact. As a result, deterministic spin-interaction-free quantum computing can be implemented in semiconductor nanostructure.

I. INTRODUCTION

Using electron spins to implement quantum information and quantum computation in semiconductor nanostructure[1,2], as one of the most important technology developments in spintronics, has received tremendous attention in recent years. Prototypical quantum computation schemes based on electron spins have been proposed using gate voltage controlled[1,3], and optically driven[4,5,6,7,8] spin-spin coupling in semiconductor quantum dots. However, achieving a tunable spin-spin interaction with a sufficiently large strength (compared to the strength of the charge Coulomb interaction) is technically difficult. A spin-interaction-free mechanism for logical operations on electron spins is therefore more desirable. Many interaction-free schemes on measurement based quantum computing have recently been proposed[9,10,11,12,13,14], but a robust, deterministic, and scalable spin-interaction-free solid-state quantum computing scheme in semiconductor nanostructure has yet to emerge.

In this paper, we propose an implementation of scalable spin quantum computation in semiconductor nanostructure without resorting to spin-spin coupling. We can generate a charge entangled state of two electrons using single electron transitions[15,16] assisted by a semiconductor multiple-quantum-dot structure consisting of two double dots, called the quantum-dot cellular automata (QCA)[17,18]. The charge entangled state is then converted into a spin entangled state using only single-spin rotations. Spin-spin interaction is not required in this implementation, and deterministic two-qubit controlled gates can be easily manipulated as well. Therefore, deterministic and scalable spin-interaction-free quantum computation can be implemented in semiconductor nanostructure.

II. ARCHITECTURE OF THE SPIN-INTERACTION-FREE QUANTUM COMPUTER

The architecture of our scalable quantum computer is based on a semiconductor multiple-quantum-dot structure schematically shown in Fig. 1. Each shaded squared box in Fig. 1 is regarded as a unit cell. Each cell contains a qubit dot (the central black dot) surrounded by four ancilla dots (the white dots). The detailed structure of a unit cell is given in Fig. 2(a). The lines between quantum dots in the cell indicate the possibility of inter-dot transitions. We assume that each unit cell is charged with only one excess conduction electron[19]. The electrostatic potential energy (ε_q) of the excess electron in the qubit dot is low enough compared to the energy (ε_a) in the ancilla dots such that the electron sits initially in the qubit dot due to the Coulomb blockade effect [see Fig. 2(b), where $\varepsilon = \varepsilon_a - \varepsilon_q$]. Explicitly, we define quantum states of the excess electron sitting in the qubit dot in each cell as a direct product of the spin-charge states, $|S_i\rangle|e_i\rangle$ $(i = 1, 2, \cdots)$, the charge states $|e_i\rangle$ are consid-

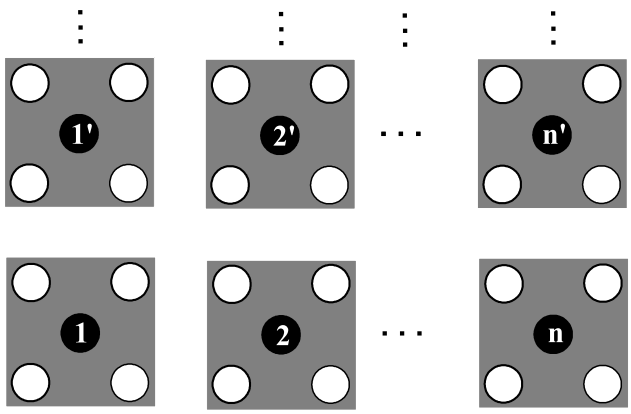

FIG. 1: A schematic architecture of the scalable spin-interaction-free solid-state quantum computer based on a multiple semiconductor quantum-dot structure.

ered as ancilla states, and the spin states $|S_i\rangle$ are chosen to be qubit states in Pauli basis, $|\uparrow\rangle = |0\rangle$ and $|\downarrow\rangle = |1\rangle$. A static uniform magnetic field can be applied to split the qubit states $|0\rangle$ and $|1\rangle$ by the Zeeman energy for qubit initialization.

Furthermore, the four ancilla dots within a unit cell are coupled to the qubit dot through gate voltages. The electron in each cell can be driven away from the qubit dot into ancilla dots only when a two-qubit controlled operation is performed, and will be forced to transit back as soon as the two-qubit operation has been completed. Such transitions are controlled using gate voltage pulses V_i^{LR}, V_i^{TB}.[15,16,20] For instance, by turning on the gate voltage V_i^{LR}, the electron will transit to a certain site (C_i or D_i) of the right two ancilla dots [see Fig. 2(c)]. We denote the charge states of the electron sitting in the ancilla dots A_i, B_i, C_i, and D_i as $|e_i^a\rangle$ with $a = A, B, C$ and D, respectively. The site dependence of electron spin state is negligible in this architecture. The effective Hamiltonian for the electron transition between the qubit dot and ancilla dots can take the form[21]

$$H_i = \varepsilon(t)(|e_i^a\rangle\langle e_i^a| - |e_i\rangle\langle e_i|) + \Delta(|e_i^a\rangle\langle e_i| + |e_i\rangle\langle e_i^a|), \quad (1)$$

where $\varepsilon(t) = \varepsilon - V_i^{LR}{}^{TB}(t)$ and Δ a tunneling coupling.

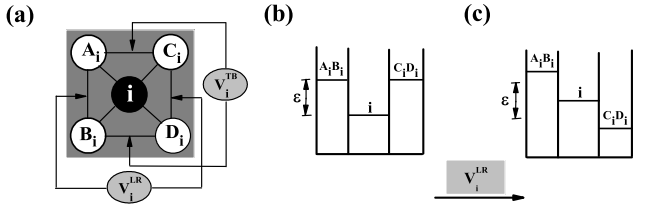

FIG. 2: (a) The nanostructure of the unit cell i. The gate voltages V_i^{LR} and V_i^{TB} control the electron transitions among dots inside the cell, (b) and (c) show the electrostatic potential energies of the electron at different dots in the cell, without and with applying a gate voltage V_i^{LR}, respectively.

Based on the above architecture, one can find that the two double-dot pairs (e.g., C_i-D_i and A_j-B_j in Fig. 3) between the qubit dots of two neighboring cells form a QCA. QCA was originally proposed as a transistorless alternative to digital circuit devices at nanoscale[17,18]. Recently, semiconductor QCA has been fabricated from GaAs/AlGaAs heterostructures[22] and from buried dopants[23] as well. Due to the Coulomb repulsion, when a QCA is charged with two electrons, these two electrons will occupy one of the two antipodal sites (called the charge polarization states denoted by $|+\rangle = |e_i^D e_j^A\rangle$ and $|-\rangle = |e_i^C e_j^B\rangle$, respectively). After a second-order perturbation treatment, the effective Hamiltonian of the QCA is then given by[24]

$$H_{\mathrm{QCA}} = (\omega + E_{\mathrm{bias}})P_z + \gamma P_x, \quad (2)$$

where $P_z \equiv \frac{1}{2}(|+\rangle\langle+| - |-\rangle\langle-|)$ and $P_x \equiv \frac{1}{2}(|+\rangle\langle-| + |-\rangle\langle+|)$, ω represents the energy offset of the polarization states $|\pm\rangle$, coming from the on-site electrostatic potential of each dot and the Coulomb repulsion between dots, E_{bias} is an external bias polarization applied to the QCA to adjust the energy splitting of the two polarization states, and γ accounts for the tunnelings between the two polarization states controlled by gate voltages acting on the two double-dot pairs. The electron tunneling between different cells is forbidden by a built-in sufficiently high energy barrier between the two neighboring cells.

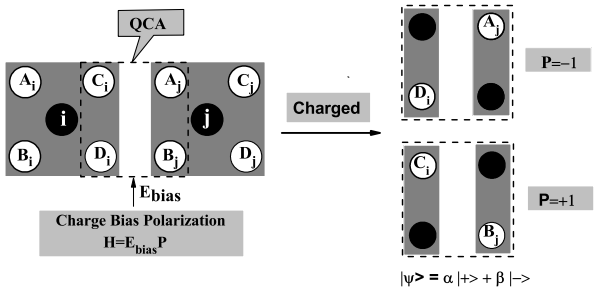

FIG. 3: Quantum mechanically, the four quantum dots (the dotted square boxes) between two qubit dots of the neighboring cells form a coherent QCA.

III. CHARGE-TO-SPIN CONVERSION OF ELECTRON ENTANGLEMENT STATES

A key to manipulate two-qubit controlled operations in this architecture is the charge-to-spin conversion of two-electron entanglement states. We shall use the QCA structure to generate a charge entangled state via single electron transitions and then convert it into a spin entangled state using single-spin rotations only. Explicitly, consider a pair of neighboring unit cells, e.g. the ith and the jth cells (see Fig. 3). The initial state of the two excess electrons is given as

$$|\Psi_0\rangle = |S_i S_j\rangle|e_i e_j\rangle. \quad (3)$$

By turning on a positive voltage V_i^{LR} and a negative voltage $-V_j^{LR}$ to lower the on-site energy of the dots C_i-D_i and A_j-B_j, the excess electrons in the two cells are transited into the QCA consisting of the double-dot pairs C_i-D_i and A_j-B_j, and occupy one of the two polarized states due to the Coulomb repulsion. To be specific, let the two electrons occupy the polarized state $|-\rangle = |e_i^C e_j^B\rangle$, that is,

$$|\Psi_0\rangle \overset{(V_i^{LR}, -V_j^{LR})_{\mathrm{on}}}{\longrightarrow} |\Psi_1\rangle = |S_i S_j\rangle|e_i^C e_j^B\rangle. \quad (4)$$

This manipulation is reliable in current experiments with passage time of a few tens of picoseconds or less[21]. A numerical simulation of electron transitions based on Eq. (1) is presented in Fig. 4 (also refers to[25]).

To generate a charge entangled state through the QCA structure, we may adjust the external bias E_{bias} to make the two polarized states degenerate (i.e., $E_{\mathrm{bias}} = -\omega$), and then apply a $\frac{\pi}{2}$ gate voltage pulse (with a pulse time

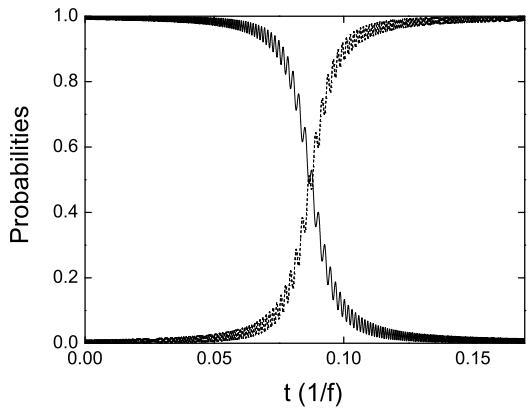

FIG. 4: Numerical simulation of electron transition from a qubit dot to an ancilla dot based on Eq. (1), with $V_i^{LR} = A\sin(2\pi ft)$. The solid curve is the probability of electron sitting in the qubit dot during the transition and the dashed curve is that sitting in the ancilla dot. We take $\varepsilon : A : \Delta = 1 : 2 : 0.1$ and ε is of the order of meV. The transition can be completed in tens of picoseconds with a very high fidelity (>0.99).

$\tau_p = \frac{\pi}{2}/\gamma$) to turn on the tunneling γ between the two polarization states. The state $|\Psi_1\rangle$ thus becomes

$$\begin{aligned} |\Psi_2\rangle &= U_{\rm QCA}(\tau_p)|\Psi_1\rangle = e^{-iH_{\rm QCA}\tau_p}|\Psi_1\rangle \\ &= |S_iS_j\rangle\frac{1}{\sqrt{2}}\big(|e_i^Ce_j^B\rangle - i|e_i^De_j^A\rangle\big). \end{aligned} \quad (5)$$

This superposition state is indeed a maximally entangled charge state. Note that the current technique enables us to have nearly identical dots for electronic tunneling[20,21]. As long as no observable difference reflected in tunneling, the dots in our design are not required to be fully identical. Meanwhile, if the pulse duration τ_p (in picoseconds, see the discussion later) can be accurate to femtoseconds, a very high fidelity of Eq. (5), $F = \cos^2(\gamma\delta t) \sim 1 - 0.002$, is obtainable.

Now, we shall convert the charge entangled state into a spin entangled state using only single-spin rotations. Single-spin manipulations in a single or double dots have been extensively explored through voltage controls of a local magnetic field and the local g factor within nanoseconds[26] or using ultrafast optical pulses up to picoseconds and femtoseconds[27,28]. Explicitly, consider the initial spin state of the two electrons, $|S_iS_j\rangle = |\uparrow\downarrow\rangle = |01\rangle$. Applying two spin rotations on the electrons sitted at the dots D_i and A_j, respectively, $U_S^{DA} \equiv R_y^A(\pi) \otimes R_x^D(\pi)$, where $R_k(\theta) \equiv \exp(-i\theta\sigma_k/2), k = x, y, z$, the corresponding two-electron spin state at the dots D_i and A_j becomes $U_S^{DA}|01\rangle|e_i^De_j^A\rangle = -i|10\rangle|e_i^De_j^A\rangle$, while the spin state at the dots C_i and B_j remains unchanged: $U_S^{DA}|01\rangle|e_i^Ce_j^B\rangle = |01\rangle|e_i^Ce_j^B\rangle$. After the spin rotation operations, we turn off the gate voltages V_i^{LR} and $-V_j^{LR}$, the two electrons in the QCA are transited back into the qubit dots i and j, namely, the electron charge states return to the initial states,

$$\begin{aligned} |\Psi_3\rangle = U_S^{DA}|\Psi_2\rangle &= \frac{1}{\sqrt{2}}\big(|01\rangle|e_i^Ce_j^B\rangle - |10\rangle|e_i^De_j^A\rangle\big) \\ &\stackrel{(V_i^{LR},-V_j^{LR})_{\rm off}}{\longrightarrow} \frac{1}{\sqrt{2}}\big(|01\rangle - |10\rangle\big)|e_ie_j\rangle. \end{aligned} \quad (6)$$

As a result, the electron charge entangled state has been converted completely into the spin entangled state, the Bell state $|\psi^-\rangle$. This is the implementation of charge-to-spin conversion of a two-electron entanglement state. Repeating the process of Eqs. (3-6) with different initial spin states $|10\rangle, |00\rangle$, and $|11\rangle$, we obtain

$$\overbrace{U_S^{DA}U_{\rm QCA}(\tau_p)}^{(V_i^{LR},-V_j^{LR})} \begin{cases} |10\rangle|e_ie_j\rangle \\ |00\rangle|e_ie_j\rangle \\ |11\rangle|e_ie_j\rangle \end{cases} = \begin{matrix} \frac{1}{\sqrt{2}}\big(|10\rangle + |01\rangle\big)|e_ie_j\rangle \\ \frac{1}{\sqrt{2}}\big(|00\rangle - |11\rangle\big)|e_ie_j\rangle \\ \frac{1}{\sqrt{2}}\big(|11\rangle + |00\rangle\big)|e_ie_j\rangle, \end{matrix} \quad (7)$$

namely, the other three spin Bell states $(|\psi^+\rangle, |\phi^-\rangle, |\phi^+\rangle)$ can be generated from the same quantum operations.

IV. THE SPIN-INTERACTION-FREE QUANTUM COMPUTING AND DECOHERENCE ANALYSIS

Once we can convert charge entangled states into spin entangled states, manipulating a two-qubit gate for electron spin qubits is relatively simple. Consider the CNOT gate as an example. Instead of using the spin rotation U_S^{DA} in Eq. (6), we should apply a single spin rotation on each dot C_i, D_i, A_j, and B_j in the QCA with the rotation operator $U_S^{CDAB} = R_x^B(\frac{\pi}{2}) \otimes R_x^A(\frac{3\pi}{2}) \otimes R_z^D(\frac{3\pi}{2}) \otimes R_z^C(\frac{\pi}{2})$ to rotate the corresponding electron spin state in $|\Psi_2\rangle$. Using the same process of Eqs. (3-6) with the above replacement of the spin rotations, we have

$$\overbrace{U_S^{CDAB}U_{\rm QCA}(\tau_p)}^{(V_i^{LR},-V_j^{LR})}|\Psi_0\rangle = U_{\rm CNOT}|\Psi_0\rangle. \quad (8)$$

It is easy to check that Eq. (8) gives explicitly the CNOT gating: $|00\rangle|e_ie_j\rangle \to |00\rangle|e_ie_j\rangle$, $|01\rangle|e_ie_j\rangle \to |01\rangle|e_ie_j\rangle$, $|10\rangle|e_ie_j\rangle \to |11\rangle|e_ie_j\rangle$, and $|11\rangle|e_ie_j\rangle \to |10\rangle|e_ie_j\rangle$. Thus, a spin two-qubit CNOT gate is manipulated using only single-spin rotations and single electron transitions assisted with the QCA structure. Combining the spin two-qubit CNOT gate with single spin rotations, universal quantum computation has been achieved without resorting to spin-spin coupling for the first time.

Meantime, the qubit state readout in this scheme can be realized as follows. A single-shot readout of electron spin states in qubit dot can be realized by coupling the unit cell to a quantum point contact (QPC). Explicitly, one can tune a gate voltage pulse, e.g., V_i^{LR}, to lower the on-site energy of dots C_i, and D_i such that the electron will remain in the qubit dot if it is in the state $|0\rangle$;

otherwise, the electron will transit to the dots C_i and D_i and then return to the qubit dot after the pulse if it is in the state $|1\rangle$. Thus, one can read-out qubit states by measuring charge current changes through the QPC channel. Such a measurement has been experimentally demonstrated in semiconductor dots[29] and theoretically studied extensively[30,31].

The possible imperfection in the above manipulation may come from decoherence and inaccurate operations on electron states. The effect of gate voltage pulses on the electrically floating double dots involves an abrupt change in the confinement potential and modifies Δ, ω as well as ε, γ in Eqs. (1-2). Combining with the noises from the electron-phonon interaction and piezoelectric coupling results in a typical charge decoherence time $T_2 \sim 1 - 10$ ns in GaAs dots[21]. The decoherence could not affect the transition of Eq. (4) since the tunneling only occurs near the resonance region $\varepsilon(t) \sim 0$ in picoseconds (see Fig. 4). For the operation in (5), the tunneling coupling inside the QCA should be controlled with the requirement, $Ke^2/r < \gamma < Ke^2/d$, where $K = 6.9 \times 10^8 N \cdot m^2/C^2$ for GaAs, e is the electron charge, and $r = \sqrt{2}d$ with d the spacing between A_j (C_i) and B_j (D_i). Direct calculation for $d \sim 50 - 100$ nm shows that γ is of the order of terahertz. Accordingly the operation in (5) could also be done within picoseconds, much shorter than the charge decoherence time in double dots.

Since the charge decoherence time is only a few nanoseconds short, a very fast and elaborately operated single-spin rotation is required for single spin rotations in Eqs. (6) and (8). Recent experiments demonstrated that optical tipping pulses with a frequency below the band gap of the semiconductor nanostructure can create an effective magnetic field in the order of 20 T via the optical Stark effect, which can induce substantial rotations of electron spins at the femtosecond scale[28]. Meanwhile, spin-flip Raman transitions using the adiabatic process of two ultrafast laser pulses[27] can also fully control single-spin rotations in semiconductor quantum dots at picosecond or femtosecond scale[32]. These optical controls of single spin rotations are technically very supportive for a practical implementation of the present scheme.

As an overall decoherence analysis, recent measurements in GaAs and In(Ga)As quantum dots have shown a long spin relaxation time ($T_1 \sim 1 - 20$ ms)[33], the spin decoherence time (T_2) in GaAs dots caused by the complicated nuclear spin fluctuation is about 10 ns[34,35]. A lower bound on the spin coherence time exceeding 1 ms has also been established using spin-echo techniques on two electrons in double dots[35], while the charge decoherence time is a few ns[21] and maybe up to 200 nanoseconds in isolated silicon double dots[20]. If the manipulation of single electron transitions and single-spin rotations can be completed within picoseconds to femtoseconds, the implementation of spin-interaction-free quantum computation with quantum error correction is reliable in experiments.

V. SUMMARY

In summary, without resorting to spin-spin coupling, we have proposed a deterministic and scalable spin quantum computing scheme assisted by a semiconductor multiple-quantum-dot structure. Spin-interaction-free solid-state quantum computing is a big challenge, in principle. In this scheme, we are able to achieve such an implementation basically relying on the charge-to-spin conversion of electron entanglement states with the help of the QCA. The QCA structure offers an intrinsic charge coupling of two electrons, which is more effective, completely deterministic, and scalable in comparison with the measurement based quantum computing scheme in semiconductor nanostructure[12]. Since spin couplings are much weaker than the charge Coulomb interaction, such a spin-interaction-free quantum computing has the advantage of being robust against the technical difficulties of electronically or optically generating tunable spin-spin couplings[1,3,4,5,6,7,8]. The present scheme only involves gate voltage controls of electron transitions and the optical manipulation of spin coherence in semiconductor dots. These techniques are currently reliable in experiments. Therefore, the spin-interaction-free quantum computing can be realized practically in semiconductor nanostructure.

Acknowledgments

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